Sub-10-fs, terawatt-scale Ti:sapphire laser system

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A three-stage, 1-kHz amplifier system delivering pulses shorter than 10 fs with a peak power in excess of 0.3 TW is reported. Passive and active spectral intensity and phase control allows the preservation of a bandwidth of 120 nm (FWHM) to as high as multimillijoule energy levels and temporal compression of the broadband pulses close to their Fourier limit. The system is scalable to peak powers well beyond 1 TW and holds promise for substantially advancing the state of the art of coherent laboratory soft-x-ray sources.

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High-peak-power laser systems based on the concept of chirped-pulse amplification[1] are now commonplace in modern laser laboratories and permit studies of light–matter interactions under extreme conditions. One of their major applications has been the generation of coherent ultraviolet and soft-x-ray radiation by means of high-order harmonic generation. Extension of this radiation to photon energies of several hundred electron volts at useful flux levels requires kilohertz-repetition-rate sub-10-fs pump sources with peak powers approaching the terawatt level. The ultrashort duration of such pulses benefits both the conversion efficiency[2] and the confinement of the emission into an isolated subfemtosecond pulse.[3] Ti:sapphire-based high-power laser systems have been demonstrated to be capable of delivering pulses of the required peak power at kilohertz repetition rates.[4–13] However, the pulse duration was limited to ~20 fs in all these systems by a dramatic narrowing of the gain bandwidth during the preamplification process.

In this Letter we report what is to our knowledge the first high-power Ti:sapphire laser capable of producing ultrashort pulses with duration not restricted by gain narrowing. As a result, terawatt-scale sub-10-fs pulses are generated at a repetition rate of 1 kHz.

The laser system (Fig. 1) contains three multipass Ti:sapphire amplifier stages and is seeded by a Ti:sapphire oscillator (Femtosource Compact Pro, Femtolasers GmbH). The first stage implements nine passes through a Ti:sapphire crystal placed in the focus of two curved mirrors with radii of curvature of −400 and −600 mm (for details of the layout see Refs. 5 and 9). This stage is pumped by half of the 20-mJ pulse energy of a Q-switched, frequency-doubled Nd:YLF laser (Thomson CSF 621D) at a 1-kHz repetition rate. The other half is used to pump the second stage. The Ti:sapphire crystal has a length of 8 mm and absorbs 90% of the pump beam passed twice through the gain medium. The diameters of the pump and seed beams in the amplifier crystal are ~400 and ~300 μm, respectively. The energy of the pulses is boosted to 1 mJ, and gain

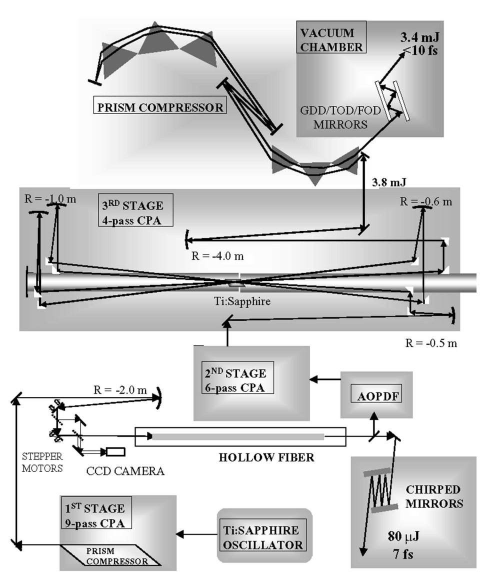

Fig. 1. Experimental setup of the three-stage amplifier system. GDD, group-delay dispersion; TOD, third-order dispersion; FOD, fourth-order dispersion; CPA, chirped-pulse amplification.

narrowing is partially compensated for[9,13] by thin-film dielectric filters that are inserted into the first eight passes. Figure 2 depicts the spectrum of the output pulses with and without spectral filtering and the transmission of the inserted filter after eight passes.

The amplified 60-nm-bandwidth pulses are recompressed in a LAK16A double-prism compressor[13] with 1.7-m prism separation after the first stage and with chirped mirrors located between the oscillator and the amplifier to precompensate the excessive negative third- and fourth-order dispersion of the prism compressor by 62 reflections. The chirped mirrors nominally introduce a third-order dispersion of 600 fs^3 and a fourth-order dispersion of 1800 fs^4 per bounce. Careful optimization of the number of reflections and the parameters of the prism compressor have resulted in pulses compressed close to their Fourier limit of ~20 fs.

To provide sufficient bandwidth for compression below 10 fs, the pulses are launched into a hollow-core fiber (length, 0.5 m, core diameter, 200 μm) filled with argon at a pressure of 0.6 bar.[14] The direction of the laser beam is monitored at two different positions with a CCD camera (Fig. 1). Deviations from the ideal beam direction are corrected with a pair of motorized mirror mounts controlled by a computer-assisted feedback loop. The pulses enter the waveguide with an energy of ~0.8 mJ. The coupling into the fiber was designed to guarantee long-term stability but somewhat compromises the throughput. Pulses with an energy of 0.3 mJ and spectral width of nearly 160 nm (FWHM) exit the waveguide (Fig. 3). The broadband spectrum shows a rapidly oscillating structure around 750 nm, the origin of which is not fully understood yet. After the fiber the beam is split into two parts. The slightly chirped output pulse is compressed close to its transform limit by broadband chirped mirrors, resulting in 7.6-fs pulses with a peak power of 9 GW. The spectral phase and the intensity profile (Fig. 3) are evaluated from a spectral phase interferometry for direct electric-field reconstruction[15] (SPIDER) measurement, whereas the spectrum is measured separately by a spectrograph. These preamplified few-cycle pulses are well suited for a wide range of strong-field experiments.

The other part of the spectrally broadened pulses are again stretched temporally by passing them through a 5-cm-long SF57 glass block, a broadband Faraday isolator (FR 780 BB, Gsänger Optoelektronik GmbH), and a newly developed acousto-optic programmable dispersive filter[16] (AOPDF) (DAZZLER, Fastlite) to a duration of 15 ps. The new prototype AOPDF can control the amplitude and phase of spectral components over a wavelength range as broad as 350 nm, with an enhanced diffraction efficiency[17] of 40%. So far, the AOPDF has been used primarily for compensating residual high-order phase errors and flattening the effective gain profile for subsequent amplification (Fig. 2). The beam exiting the waveguide is matched with a telescope to the 4-mm clear aperture of the AOPDF and the input of the second amplifier stage. The task of this six-pass amplifier stage (double-pass absorption, 90%) is to compensate for the losses previously suffered by the pulses upon spectral broadening and shaping. This amplifier stage consists of two confocal, broadband chirped mirrors with radii of curvature of −400 and −600 mm. The 4-mm-long Ti:sapphire amplifier crystal is slightly offset from the common focus of the mirrors to fit the beam diameter of the seed beam to the 400-μm beam diameter of the pump. To avoid substantial spectral narrowing, anti-gain-narrowing filters are inserted into the first four passes, and the AOPDF is programmed to introduce the spectral shaping effect shown in Fig. 2.

Finally, the pulses are passed four times through a third 8-mm-long Ti:sapphire crystal (double-pass absorption, 90%) pumped by 25-mJ pulses of a Q-switched frequency-doubled Nd:YLF laser (Photonics GM-30-527). To minimize thermal aberrations, the crystal is cooled to 150 K by a closed-loop cryostat (Cryotiger, APD Cryogenics, Inc.), which dramatically enhances thermal conductivity and decreases the temperature coefficient of the refractive index of the sapphire crystal.[4] The pump and seed beam

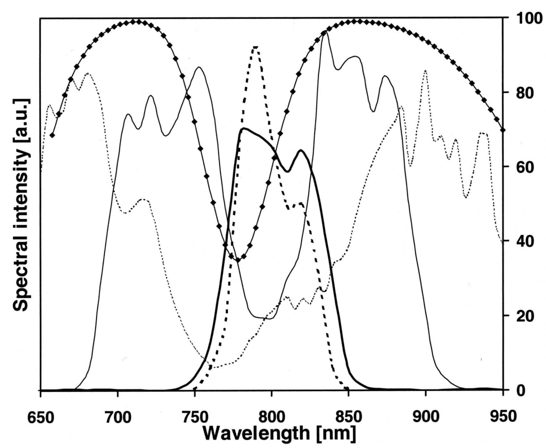

Fig. 2. Output spectrum of the first stage with (solid thick curve) and without (dashed thick curve) spectral filtering, and the transmission of the different spectral filters in the first stage (solid thin curve), in the second stage (dashed thin curve), and the AOPDF (solid curve with diamonds).

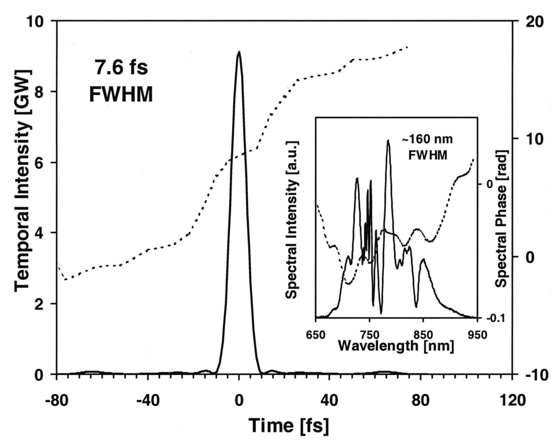

Fig. 3. Pulse shape and spectrum of the compressed fiber output (solid curves) with the corresponding phases (dashed curves) measured by SPIDER.

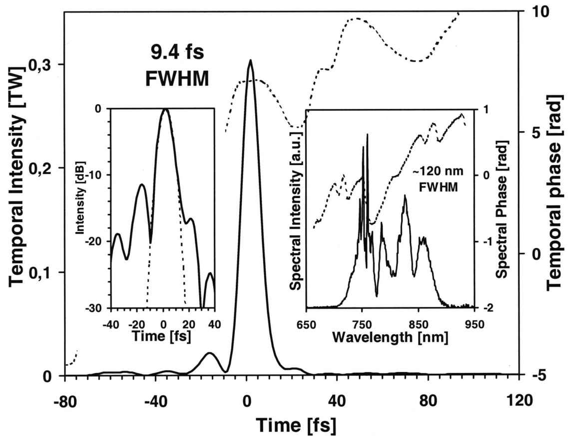

Fig. 4. Pulse shape and spectrum at the output of the three-stage amplifier system (solid curves) with the corresponding phases (dashed curves) measured by SPIDER. Left inset, pulse shape on a logarithmic scale with a Gaussian fit of the same duration (dotted curve).

diameters in the crystal are 600 and 500 μm, respectively. The pulse energy is boosted from 0.5 mJ to 3.7–3.8 mJ, corresponding to an energy extraction efficiency of 15%.

The beam exiting the third stage is collimated and expanded to a diameter of 20 mm before being injected into a prism compressor consisting of two sets of triple prisms made of fused silica to minimize high-order dispersion. The Brewster prisms at the input and in front of the retroreflecting mirror have a baseline of 100 and 150 mm, respectively. This ensures a throughput over a spectral range as broad as 200 nm for the 2.5-m separation of the prism sets. The compressor has a throughput of ~90%, resulting in compressed pulses with an energy of 3.4–3.5 mJ. Again, chirped mirrors provide coarse control of high-order dispersion. By using 24 bounces before the third amplifier stage and four reflections after the prism compressor together with fine dispersion control by the AOPDF (with parameters of $-2000\ \mathrm{fs}^2$, $+1700\ \mathrm{fs}^3$, and $+16000\ \mathrm{fs}^4$), we are able to recompress the amplified multimillijoule output pulses to a duration of 9.4 fs (−0.3 + 0.6 fs). This pulse width has been evaluated from SPIDER (Fig. 4) analysis[17] and confirmed by an interferometric autocorrelation measurement. Some 90% of the total pulse energy is carried within a central feature that fits well to a Gaussian pulse shape (see left inset in Fig. 4), with the remaining part scattered over an interval of some ±100 fs. The chirped mirrors implementing the final compression (by a factor of ~6) are placed into a vacuum chamber to avoid wave-front distortions by nonlinear propagation effects in air. The M^2 of the subterawatt laser beam is evaluated as 1.5/1.8, indicating a near-diffraction-limited output. The warm-up time of the system is approximately 2–3 h, which is dictated primarily by that of the pump lasers, after which the system output remains stable until the laboratory temperature remains constant to within ±2 °C.

In summary, we have developed a Ti:sapphire amplifier system delivering sub-10-fs pulses with a peak power of 0.3 TW in a near-diffraction-limited beam. The new source is expected to allow the generation of powerful high-order harmonic radiation to as high as photon energies in the water window and extend attosecond time-resolved spectroscopy into this important spectral range. The envisaged upgrade of the system to peak powers exceeding 1 TW will open the way to few-cycle relativistic electron–light interactions.

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